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ABSTRACT

Detailed numerical prototypes are essential to the design of efficient and cost-effective neutron and gamma-ray imaging systems. We have exploited the unique capabilities of an LLNL-developed radiation transport code (COG) to develop code modules capable of simulating the performance of neutron and gamma-ray imaging systems over a wide range of source energies. COG allows us to simulate complex, energy-, angle-, and time-dependent radiation sources, model 3-dimensional system geometries with "real world" complexity, specify detailed elemental and isotopic distributions and predict the responses of various types of imaging detectors with full Monte Carlo accuracy. COG references detailed, evaluated nuclear interaction databases allowing users to account for multiple scattering, energy straggling, and secondary particle production phenomena which may significantly effect the performance of an imaging system but may be difficult or even impossible to estimate using simple analytical models. In this work we will present examples illustrating the use of these routines in the analysis of industrial radiographic systems for thick target inspection, nonintrusive luggage and cargo scanning systems, and international treaty verification.

Keywords: numerical modeling, radiation transport, nonintrusive inspection, neutron imaging, photon imaging

1. INTRODUCTION

The development of reliable techniques to simulate radiation transport in complex experimental situations has been essential to the success of many programs at Lawrence Livermore National Laboratory (LLNL) over the past forty years. During that time, researchers at our facility have developed unique expertise in the combined numerical and experimental simulation of systems ranging in complexity from highly specialized underground nuclear test diagnostics to commercial nonintrusive inspection systems. Based on our experience, we are convinced that detailed numerical modeling provides a much more accurate estimate of the actual performance of complex experimental systems than does simple analytical modeling. Furthermore, the development of numerical prototypes allows system designers to quickly explore the full parameter space available to them before committing their ideas to hardware. This approach has frequently lead to improvements in experimental designs at LLNL and reductions in overall system development costs.

In this work we will discuss the development of a new tool for doing full Monte Carlo modeling of neutron and gamma-ray imaging systems and present examples illustrating its use in prototyping experimental systems at LLNL. The examples will include the analysis of industrial radiographic systems for thick target inspection, nonintrusive luggage and cargo scanning systems, and international treaty verification.

2. NUMERICAL TECHNIQUES

During the early 1980's, researchers at LLNL set out to develop a modern, full-featured radiation transport code which could exploit the power of the newer, high-speed Cray computers then coming on line. The result, released to the local community in the mid-1980's, was COG (so named after an old-English slang term referring to "a trick of the dice").[1] COG is a detailed, high-resolution Monte Carlo neutron and photon transport code capable of providing accurate answers to complex deep-penetration (or shielding) problems. Unlike many of its predecessors, COG is free of the physics compromises and approximations traditionally used in radiation-transport calculations. COG is fully three-dimensional, uses point-wise-correct cross-sections and angular scattering functions, and provides the user with a full range of statistical biasing options to speed up problem convergence. Problem geometries can be set up manually using simple but powerful constructs (more than 30 complex pseudo-surfaces such as boxes, spheres, cylinders, and cones are included in COG's geometry package as elementary types) or developed using CAD tools and then transformed automatically into the proper input format. System components can be visualized in both cross-sectional and perspective views to assure their fidelity and complex geometries can be debugged on a standard Macintosh workstation. COG allows users to score the results of a simulation using one or more of its standard built-in detector types (*e.g.* boundary crossing detectors, reaction detectors, point flux estimators, and pulse detectors) as well as specialized, user-written detector packages linked in at run time.

We have recently exploited the unique scoring capabilities offered by COG to develop user-written detector packages capable of simulating the performance of neutron and gamma-ray imaging systems over a wide range of source energies. Using these routines, users can now define one or more rectangular “imaging detectors” within the problem geometry and obtain high-resolution radiographic images with full Monte Carlo accuracy at the specified locations. The imaging areas may be broken up into an arbitrary number of rectangular pixels (the current packages limit arrays to 100 X 100 pixels in order to keep output file sizes below ≈ 500 k) and detector scoring may be controlled by using energy, time (particle age), angle and number-of-collision masks just as with other COG detectors. Several different detector modes (scoring options) have been implemented in order to simulate various types of imaging detectors. These include a boundary crossing mode (counts, particle flux, or energy flux), track length mode (similar to COG’s reaction detector), and total energy deposition mode. Imaging detectors are specified along with any of the normal COG detectors in the DETECTOR block of the input deck using a simple formalism (7 - 12 lines depending on the desired detail) consistent with COG’s standard input format. COG handles all required image pre-processing and returns a tab-delimited ASCII file with detailed counting statistics on each pixel in the array which can then be read with any standard image processor (*e.g.* Spyglass, IPLab, etc.).

The ultimate accuracy of a numerical simulation is limited only by the accuracy of the data contained in its reference libraries. COG is capable of accessing either of two well-known cross-section databases, LLNL’s Evaluated Nuclear Data Library (ENDL-90) or the Evaluated Nuclear Data File (ENDF/B-V), to determine the probability of a particle interacting with the medium through which it is transported. The use of detailed, evaluated nuclear interaction databases such as these allows users to account for multiple scattering, energy straggling, and secondary particle production phenomena which may significantly effect the performance of an imaging system but which may be difficult or even impossible to estimate using simple analytical models. COG’s accuracy and reliability have been proven through extensive benchmarking on radiation shielding and criticality problems relevant to recent LLNL programs.[2]

Several major enhancements to COG have recently been implemented. Most notable among these are the addition of electron transport capabilities using a seamless interface with the EGS electron transport code[3] (links to a high energy, all particle transport code are also being planned) and adaptation of the code for use in multi-processor (PVM) environments (essential for high-resolution imaging problems). In addition, the code has been adapted for use on the latest generation of Unix-based workstations (*e.g.* HP, Sun , IBM and SGI) as well as standard Power Macintosh desktop computers. COG is available as public-domain software to any user with the requisite computational resources.

3. MODELING EXPERIMENTAL SYSTEMS

3.1 Neutron radiography of thick targets

We have recently collaborated in experiments at the Los Alamos Nuclear Science Center (LANSCE) aimed at establishing a proof-of-principle for radiography of thick targets using very high energy neutrons (≈ 40 - 400 MeV)[4]. In those experiments, an assembly consisting of a low-Z disk with a thickness of 2.54 cm sandwiched between two 5.08-cm-thick high-Z slabs was used as a phantom target. Several small holes (4 - 12 mm) drilled all or part of the way through the disk were used to simulate defects in the low-Z material. A position-sensitive multiwire detector with a heavy metal converter was used to record the neutron image with a spatial resolution of ≈ 1 mm. Since neutron interaction cross sections do not scale strongly with Z, neutron radiography is sensitive to detect defects such as these in low-Z materials even when those materials are heavily shielded by high-Z parts (a difficult task for conventional photon radiography); thus, neutron radiography has the potential to be a powerful nonintrusive inspection tool for thick targets.

During the course of these experiments, we took the opportunity to use COG to simulate the result that would be obtained if the LANSCE phantom target were imaged using lower energy (14 MeV) neutrons from a commercially available source. The geometrical model used in the simulation and the resultant image (resolution ≈ 1 mm) are shown in Figure 1. This image is the result of a 100M particle run executed in parallel under PVM with 9 slaves on three different platforms. Based on a favorable comparison with the high energy LANSCE image, we have recently launched a program to develop neutron imaging systems operating in the 10 - 15 MeV energy range.

3.2 Nonintrusive luggage and cargo scanning systems

A variety of nonintrusive inspection systems have been proposed over the past several years for the detection of hidden contraband in airline luggage and shipping containers. The majority of these proposed techniques depend on the interaction of radiation with matter to produce signatures specific to the contraband of interest, whether illegal drugs or explosives. Almost without exception, these schemes have been based on simplified physical models which assume straight-line radiation transport and single interactions between the probe particles and the container of interest, assumptions which we have found rarely prove true in the world outside of the laboratory.

In an effort to assess the utility of different types of radiation sources in these systems, we have recently used COG to simulate a potential airport luggage scanning system. Figure 2 shows the simulated image of a particularly nefarious (and hopefully fictitious!) overnight bag irradiated by 100 keV gamma rays (resolution ≈ 2.5 mm). This image is the result of a 100M particle run executed in parallel under PVM with 11 slaves on three different platforms. It is the composite of four adjoining 100 X 100 pixel images. Simulations such as these are useful in comparing the relative material detection sensitivities of neutrons and gamma rays.

3.3 Treaty verification

The provisions of the Intermediate-Range Nuclear Forces (INF) Treaty between the United States and the FSU have allowed on-site inspectors to install and operate an x-ray scanning system for imaging the contents of transport canisters declared to contain missiles or missile stages exiting the Votkinsk Missile Complex in Russia. The missile canisters are contained in sealed railcars with bar codes imprinted on their sides which automatically trigger the imaging system.

At the request of international arms control experts at LLNL, we used COG to model the imaging system at Votkinsk and investigate several suggestions that had been advanced to improve the image quality. Our simulations of empty and loaded missile canisters within the railcar (not shown here due to space limitations) were used to study simple background subtraction techniques and the effectiveness of using energy-differential detectors.

4. SUMMARY COMMENTS

The development of effective neutron and gamma imaging systems is clearly a challenging problem. We believe that detailed numerical simulations can be an extremely valuable tool in prototyping such systems. Many fundamental issues such as detection probability, false alarm rate and throughput rate, which previously could only be determined in an operational setting, can now be accurately (and objectively) estimated using powerful radiation transport codes such as COG. Numerical modeling allows system designers to optimize system design, estimate radiation doses to system operators, and evaluate methods for interpreting signals. In short, we believe that numerical modeling can help designers develop more effective systems in less time and often at a lower overall cost.

5. ACKNOWLEDGMENTS

We would like to thank R. Buck and E. Lent of L-Division for their contributions to the description of the radiation transport code COG provided in Section 2 of this work and for their continued agility in responding to the ever-changing demands of the numerical modeling community at LLNL.

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6. REFERENCES

[1] T. Wilcox and E. Lent, *COG - A Particle Transport Code Designed to Solve the Boltzman Equation for Deep-Penetration (Shielding) Problems, Vol. 1 Users Manual*, LLNL Rept. # M-221-1 (1989); see also R. Buck and E. Lent, “COG: A New, High-Resolution Code for Modeling Radiation Transport,” LLNL Energy and Technology Review (June 1993); additional information on COG may be obtained by contacting the author of this work directly or by sending e-mail to “COG@LLNL.GOV” via the INTERNET computer network.

[2] T. Wilcox and E. Lent, *COG - A Particle Transport Code Designed to Solve the Boltzman Equation for Deep-Penetration (Shielding) Problems, Vol. 4: Benchmark Problems*, LLNL Rept. # M-221-4 (1989).

[3] W. Nelson, H. Hirayama, and D. Rogers, *The EGS4 Code System*, Stanford Linear Accelerator Center, Stanford University, Stanford, CA, Rept. 265 (December 1985).

[4] A. Gavron, *High Energy Neutron Radiography - Observing the LiD*, P-23 (Los Alamos National Laboratory) memorandum written on behalf of A. Bridge, C. Morris, M. Murray, S. Seestrom, J. Ullmann, W. Abfalterer, and A. Gavron of LANL and F. Dietrich and T. Wenaus of LLNL (December 7, 1994).

7 COLLECTED FIGURES

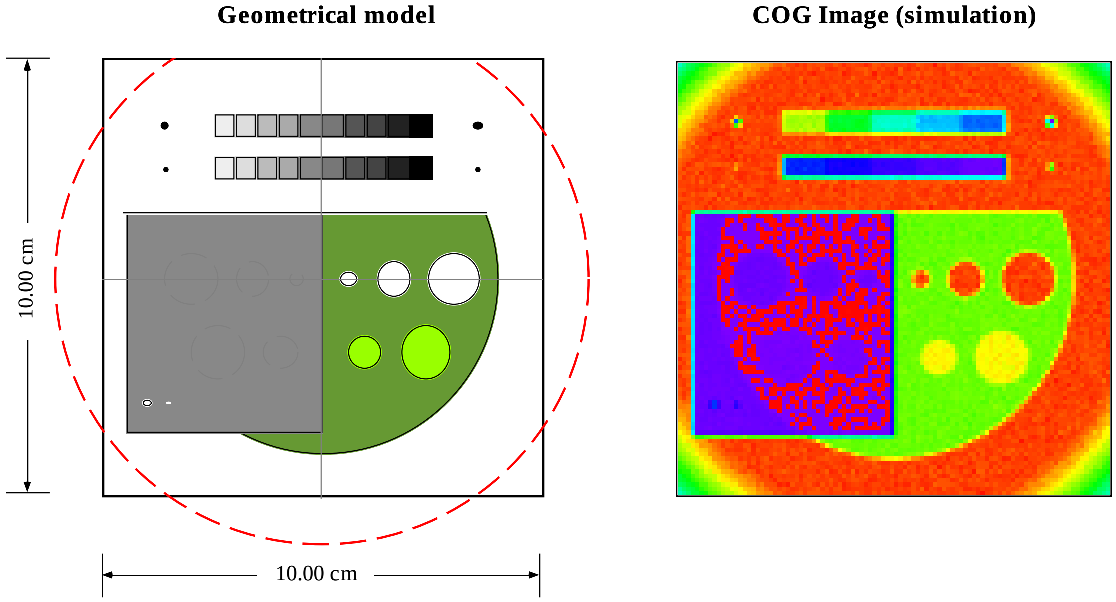
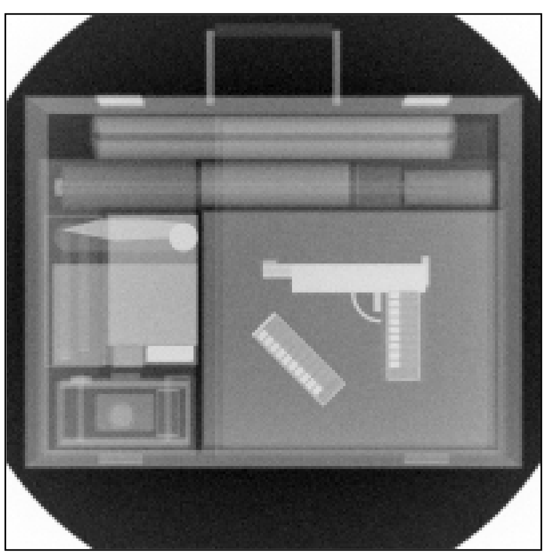


Figure 1: This figure shows the geometrical model used in our simulations of a high energy (≈ 40 - 400 MeV) neutron radiography experiment carried out recently at LANSCE (LANL). The dashed line on the left indicates the beam exposure area. The corresponding COG image for the case of 14 MeV neutrons is shown on the right. This image is the result of a 100M particle run executed in parallel under PVM on three different platforms.

Terrorist Overnight Bag
(100 keV γ; 2.5 mm resolution)



Contents:

- newspaper
- sugar container
- cocaine stash
- travel umbrella
- switchblade knife
- paperback book
- plastic explosive
- pen and pencil set
- electronic camera
- automatic pistol
- various clothing
- flat notebook

Figure 2: This figure shows the COG image of one particularly nefarious overnight bag simulated during our study of airport luggage scanning systems. The bag itself is a standard aluminum shell (≈ 40 X 30 X 10 cm) with a wood handle, thick cloth covering and steel fittings. This image is the result of a 100M particle run executed in parallel under PVM on three different platforms. It is the composite of four adjoining 100 X 100 pixel images.